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# Evaluation of the Mississippi State University Computational Fluid Dynamics Code (UNCLE)

By
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This report documents efforts, to date, in the transition of the Mississippi State University (MSU), incompressible Reynolds-Averaged Navier-Stokes code (UNCLE). The code is evaluated through replication of previous cases documented by MSU and computation of new cases that include more realistic geometries. A grid-sensitivity study is performed, in which a series of grid types and grid distributions is examined. Comparisons of the computed results with measured data for two submarine hulls are presented.

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## CONTENTS



## FIGURES

## ABSTRACT

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## ADMINISTRATIVE INFORMATION

This report is submitted in partial fulfillment of milestone 5, Exercise Unsteady RANS Codes-Validation, of Subtask 3, CFD Maneuvering Predictions, in the Manuevering and Seakeeping Project (R2332-MS1), in the Submarine Technology Program Plan (Program Element 0602121N) for fiscal year 1996. The work described herein was sponsored by the Office of Naval Research (ONR 333) and performed by the Carderock Division, Naval Surface Warfare Center, Code 5420 under Work Unit Number 1-5060-643.

## INTRODUCTION

The David Taylor Model Basin (CarderockDiv, NSWC) is tasked with transitioning the computational fluid dynamics (CFD) code developed at Mississippi State University (MSU) to the Navy. This code is an unsteady, incompressible, Reynolds-Averaged Navier-Stokes (RANS) code (UNCLE). It is being developed for use in analyzing the flow physics and subsequent forces and moments involved with a submarine under-going a manuever. UNCLE has been tested, at MSU, on various simplified geometries that are of interest to the Navy[1-6]. However, it is critical that the Navy develop an expertise and confidence in the application of UNCLE to current Navy problems.

The first step in the transition process is to determine which test cases to use. One could push the envelope and try a fully appended submarine undergoing a manuever, but it would be very taxing on the user and may provide little insight into the accuracy of the code. A better choice would be to use simplified, but realistic geometries that have a detailed experimental data base to compare against. This approach allows the user to become familiar with the code and validates the accuracy of the code.

Two primary geometries were selected as test cases: SUBOFF bare-hull [7] and David Taylor Model Body 1, bare-hull [8]. These cases were chosen because both have a large set of experimental data and have been used extensively to validate other CFD codes[9, 10, 11]. MSU has used the SUBOFF data to validate UNCLE, so it was felt that SUBOFF would be a good first run to verify that the code was installed correctly and that the user understood the required inputs. Body 1 was selected because it is a more realistic geometry, but still relatively simple.

A grid-sensitivity study is performed as a part of the validation effort. Different types of grids and different grid resolutions are examined. This study will provide a measure of the turbulence model and its dependence on various grid topologies. It will also give an indication of what type of grid resolution is necessary to capture the physics of the flow.

This report starts with a section discussing the basic algorithm used for UNCLE. The next section will present the grids that were used followed by a section on the results. The final section will contain the conclusions and recommendations of the author.

## NUMERICAL ALGORITHM

The algorithm presented in this section is based on the solution of the unsteady, three-dimensional, Reynolds-Averaged Navier-Stokes (RANS) equations cast in artificial compressibility form [12, 13]. These equations consist of a hyperbolic system of nonlinear partial differential equations. To allow for dynamic grids and complex geometries, these equations are cast in time-dependent curvilinear coordinates [1].

To solve these equations numerically, they must first be discretized. In UNCLE, a cell-centered finite-volume scheme is used for the spatial discretization and a first-order, implicit scheme is used for the temporal discretization. Although the spatial discretization provides for various accuracies, third order spatial accuracy is used for the convective terms in this work.

A flux-difference splitting approach is used to evaluate the convective part of the numerical flux at the cell faces. This approach, termed *upwind*, is based on the Roe approximate Riemann solver [14]. Upwind schemes use the eigenstructure of the hyperbolic governing equations to dictate how the fluxes are evaluated. The MUSCL approach of van Leer [15] is used to achieve third-order spatial accuracy. The viscous fluxes are approximated by central difference as described by Gatlin [16].

The discretization of the governing equations results in a system of nonlinear, algebraic equations. The solution of these equations is obtained using a discretized Newton-relaxation method, or DNR [17]. The term, *discretized*, refers to the numerical derivative used to evaluate the Jacobians resulting from the implicit formulation. *Newton-relaxation* refers to the primary and secondary iterations used to solve the system of equations. A multiblock, multigrid acceleration technique is used to speed up the convergence of the implicit scheme [6]. An algebraic turbulence model, based on the Baldwin-Lomax model [18], is used for all calculations.

## GRIDDING

A variety of grid topologies are investigated in this study. Emphasis is put on determining the grid dependence of the UNCLE code. For the bare hull geometries, both O-grid and a combination C/H-grid topologies are considered. An example of the

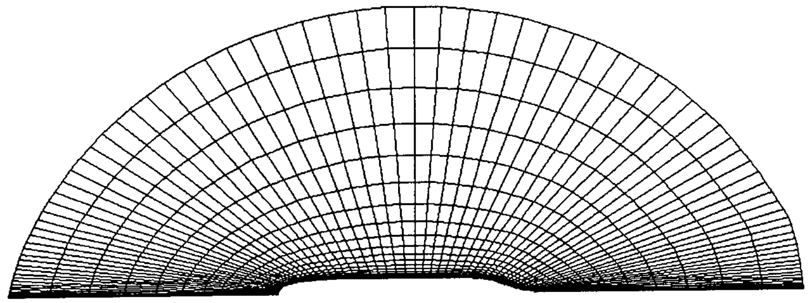

Fig. 1. SUBOFF O-Grid

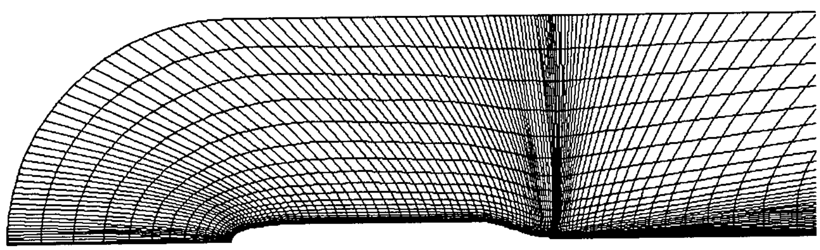

Fig. 2. SUBOFF C/H-Grid

O-grid used for the SUBOFF geometry is shown in Figure 1. The grid is packed normal to the surface and at the leading and trailing edges. For this grid, orthogonality of the grid lines emanating from the surface is not preserved.

The C/H grid topology for the SUBOFF geometry is shown in Figure 2. The C-grid wraps around the nose of the submarine and extends to the trailing edge. The H-grid continues from the trailing edge to the outflow boundary. As with the O-grid, the C-grid is packed near the hull at at the leading and trailing edges. However, orthogonality of the the grid lines with the hull is maintained as best as possible.

The different gridding approaches will test the versatility of the turbulence model in UNCLE. The C/H-grid will provide the optimal conditions for the Baldwin-Lomax model for the boundary-layer on the hull. A robust turbulence model should provide the same solution for each grid type.

The effect of grid density is also examined in this work. Various grid densities and grid distributions are presented to determine the minimum grid requirements to capture the physics.

All of the grids used for this work were generated in-house. Some of the grids were generated with a grid program developed by Joe Gorski and others with the EAGLE-View code developed at MSU [19].

## COMPUTATIONAL RESOURCES

All of the computations presented in this report were performed on the SGI R8000 installed at the Hydro Technology Center. The cpu costs can be measured as cpu seconds per grid point per time step. Using this measure, the UNCLE code requires approximately $4.78x10^{-4}$ sec/point/time step. The memory required for an $81x41x17$ grid is 122 megabytes.

## RESULTS

As stated in the introduction, two test cases are examined: SUBOFF bare-hull [7] and David Taylor Model Body 1 bare-hull [8]. The SUBOFF body is computed to ensure that the results obtained at MSU can be duplicated. A series of grids are examined to determine what the grid requirements of UNCLE are. The grid topology that works best for the SUBOFF case is then used for the DTMB Body 1 geometry.

### SUBOFF

Steady calculations of the SUBOFF geometry at zero angle of attack are compared with measured data [7]. The Reynolds number based on the length of the submarine is $1.2x10^{7}$.

For all of the cases presented here, a Courant-Friedrichs-Lewy (CFL) number of 10 is used with one multigrid V-cycle and 1 Newton iteration. The numerical Jacobians are updated every 10 time steps. A no-slip boundary condition is used on all solid surfaces. Characteristic variable inflow/outflow boundary conditions are used for the far-field boundary.

The grids shown in Figures 1 and 2 are used for the first comparison. The average $y^{+}$ off the surface is between 0.5 and 1.6 for both grids. Figure 3 contains a comparison of the convergence history for each grid. The residual for the block on the body drops approximately four orders of magnitude in 400 iterations. The residual for the second block in the C/H-grid does not drop in the same manner. This is probably due, in part, to the singularity boundary condition at the centerline of the wake. The skin friction and pressure on the hull seem to be converged by 200 iterations. The skin friction on the hull for the O-grid at 200 time steps and 400 time steps is shown in Figure 4. The difference in the two results is indiscernible.

In Figure 5, the measured and computed pressure coefficients for the O-grid and C/H-grid are compared. The results for the two grids are identical and match the measured data fairly well. A comparison of the skin friction coefficient on the hull is shown in Figure 6. A very small difference in the two solutions can be seen in this plot. Both do a reasonable job of matching the measurements everywhere but in the stern region. Although not shown, the computed results for the pressure and skin friction compare well with those obtained by MSU [5].

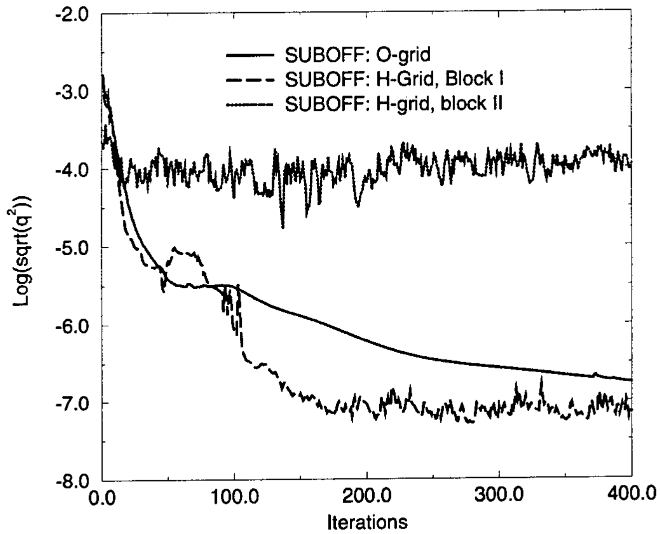


Fig. 3. Convergence of the O-grid and C/H-grid for SUBOFF.

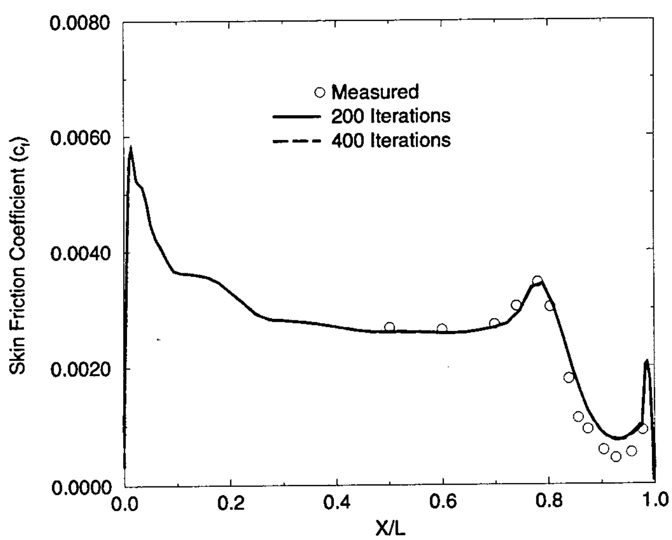


Fig. 4. Skin Friction Convergence for SUBOFF.

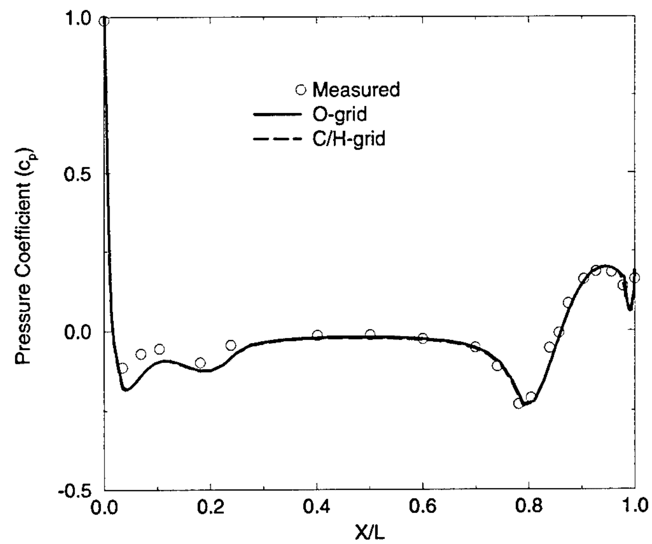


Fig. 5. Pressure Coefficient for O- and C/H-grids, SUBOFF geometry.

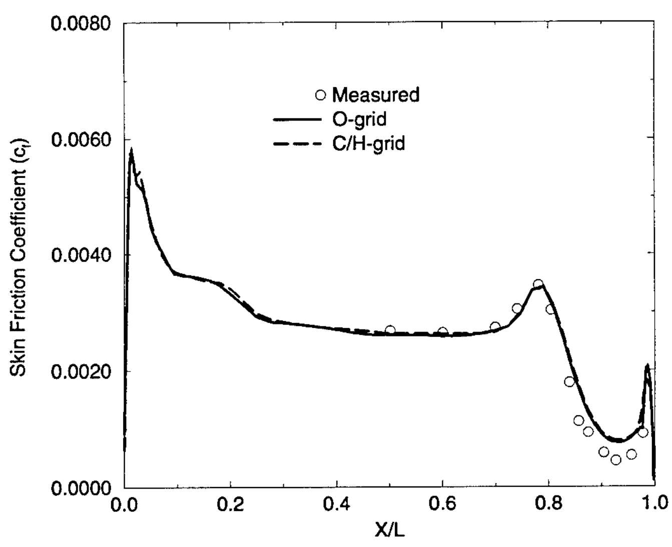


Fig. 6. Skin Friction Coefficient for O- and C/H-grids, SUBOFF geometry.

A series of grids with finer resolutions were examined to determine if the computed skin friction in the stern region could be improved. Since the O-grid and C/H-grid produced the same results, the O-grid was selected for this comparison. Fewer grid points, hence less cpu time, are required for the O-grid. The same number of points is used for each grid, however each successive grid is packed tighter to the body. The results for three grids will be shown. The $y^+$ ranges for the three grids are (1) $0.5 < y^+ < 1.6$, (2) $0.1 < y^+ < 0.5$ and (3) $y^+ < 0.1$. Since the original O-grid had a $y^+$ around 1, it should have adequately captured the pressures on the hull. Figure 7 shows the pressure coefficient on the hull for each O-grid. As expected, the solutions are identical. A comparison of the skin friction obtained using each grid is shown in Figure 8. The solution for the finest grid differs slightly from the other two grids, but not in the stern region.

Another O-grid with over double the number of points ($129x65x17$) was tried next. The comparison of the skin friction coefficient for this grid and the original O-grid is shown in Figure 9. The skin friction on the mid-body is improved, but slightly worse in the stern region. It appears that a $y^+$ in the range of 0.5 to 1.5 and grid size of $81x41x17$ will give adequate results.

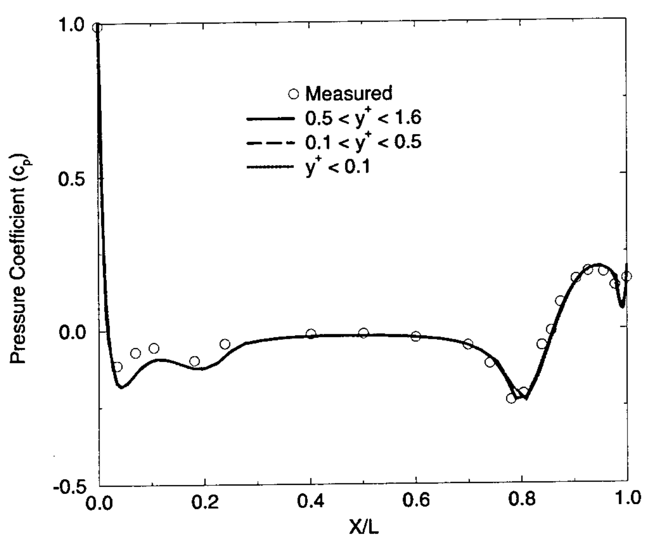


Fig. 7. Comparison of the Effect of $y^+$ on the Pressure Coefficient on the Hull, SUBOFF geometry.

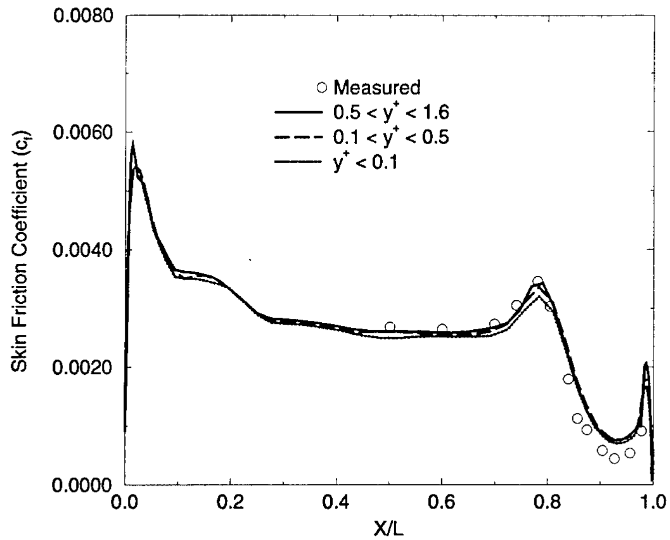


Fig. 8. Comparison of the Effect of $y^+$ on the Skin Friction Coefficient on the Hull, SUBOFF geometry.

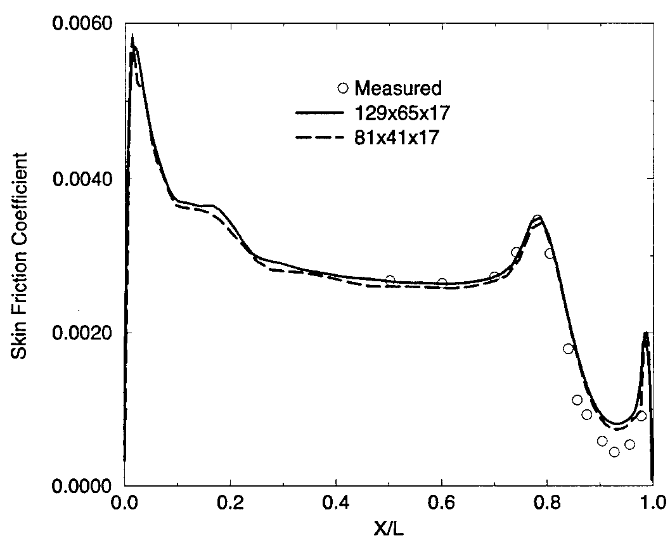


Fig. 9. Comparison of the Grid Density Effects on Skin Friction Coefficient, SUBOFF geometry.

## DAVID TAYLOR MODEL BODY 1

A comparison of measured data and computed data for David Taylor Model Body 1 is presented in this section. This body is a closer representation of real geometries being deployed by the Navy than the SUBOFF geometry. A bare-hull case at zero angle of attack operating at a Reynolds number, based on hull radius, of $3.0x10^5$ is used for comparison. Due to the success of the $81x41x17$ O-grid for the SUBOFF case, it was chosen for this case, also. A C/H-grid is also compared to see if the different grids will affect the velocities in the wake.

The O-grid is similar to that used for SUBOFF. It has dimensions of $81x41x17$ and represents a 90 degress section of the test geometry. The C/H-grid is made of two blocks. The first block contains the same number of points as the O-grid ($81x41x17$) and the second block is $33x41x17$. The $y^+$ off the surface for both grids is approximately 1-3. The same input parameters and boundary conditions are used for this case as were used for the SUBOFF case.

The convergence history for both grids is shown in Figure 10. It is very similar to that obtained for the SUBOFF case. Again, the pressures and skin friction both set up by 200 time steps. Figures 11 and 12 show the comparison of the computed and measured pressure coefficient and skin friction, respectively, on the hull. Again, no difference can be seen in the solutions between the different grids. Both computed solutions compare very well with the measured data.

Axial velocity profiles on the hull and in the wake are compared in Figure 13. The computed results for each grid are the same on the hull. A slight difference occurs in the wake region. The discrepency in the solution and measured data for the O-grid is probably due to the way in which UNCLE searches for pertinent length scales in the turbulence model. It is believed that modifying the search process slightly will improve these resulst. The discrepency may, also, be due to the interpolation routine used to extract the solution from the O-grid.

## CONCLUSIONS AND RECOMMENDATIONS

One very important point needs to be made here. The code used for this report is NOT the final MSU manuevering code. It is a stripped down version of the code used for the author's dissertation work. As such, not all of the most advanced features of the UNCLE code have been implemented.

The computed results obtained from UNCLE matched fairly well with the measured results. The skin friction and pressure calculations seem to be insensitive to the grid type used, but it seems that the velocity profiles in the wake depend on the grid. Again, this is probably due to the search algorithm used in the turbulence model. This may be corrected in the newer version of the code.

The convergence plots for the O-grid matched those presented by MSU for the single grid case. Multiple V-cycles were not run for this case to see if the solution

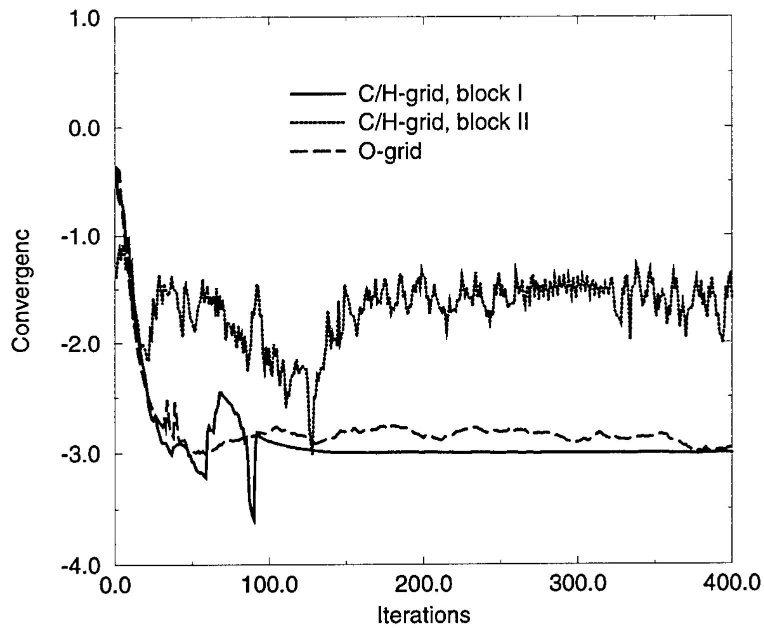


Fig. 10. Convergence of the O-grid and C/H-grid, Body 1.

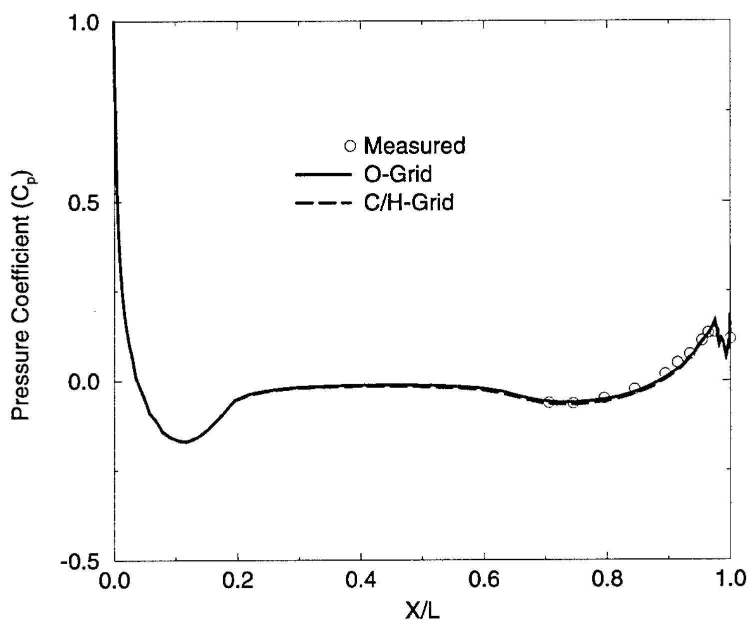


Fig. 11. Pressure Coefficient on the Hull, Body 1.

would converge to machine zero. There is some concern as to the lack of convergence of the H-block of the C/H-grid. A more thorough investigation of why this block doesn't converge should be undertaken. This problem may disappear with a newer version of the code.

One of the main problems with the code (as the author sees it) is the lack of a general boundary condition input file. The boundary conditions for each grid have to be "turned-on" in the code. For every geometry, the user must check that the desired boundary conditions are in the code and/or code them up. This is very tedious and prone to errors. This process has been automated in many other codes and needs to be done for the UNCLE code.

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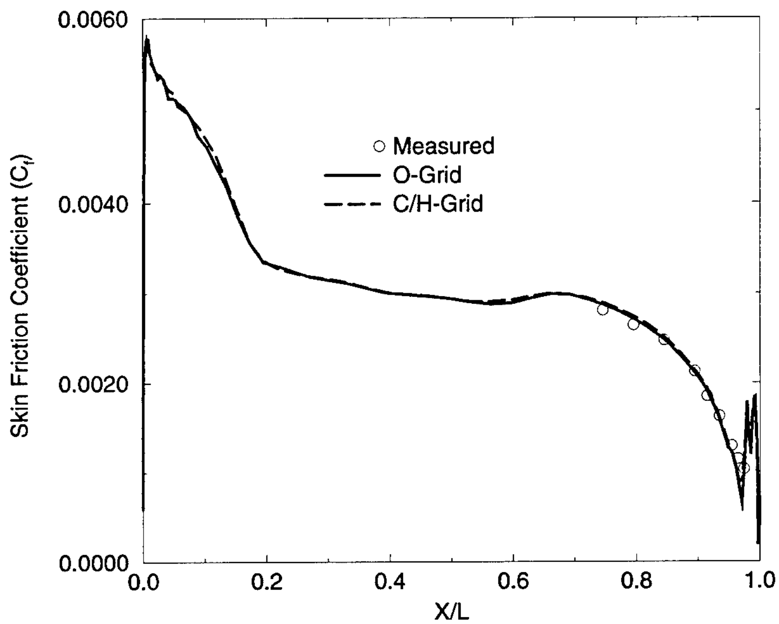


Fig. 12. Skin Friction Coefficient on the Hull, Body 1.

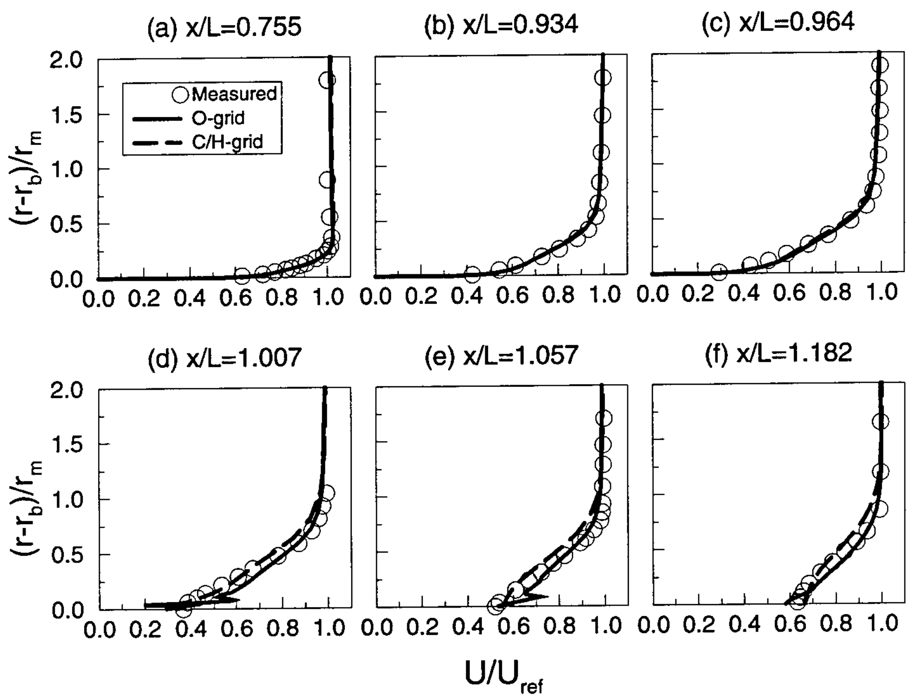


Fig. 13. Comparison of Axial Velocities, Body1

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